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Carrier Mobility in Semiconductors at Very Low Temperatures †

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Abstract: Carrier mobilities and concentrations were measured for different p- and n-type silicon materials in the temperature range 0.3–300 K. Simulations show that experimentally determined carrier mobilities are best described in this temperature range by Klaassen's model. Freeze-out reduces the carrier concentration with decreasing temperature. Freeze-out, however, depends on the dopant type and initial concentration. Semi-classical calculations are useful only for temperatures above 100 K. Otherwise quantum mechanical calculations are required.

Keywords: silicon; carrier mobility; carrier concentration; low-temperature measurements

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1. Introduction

There is a growing interest on low-temperature applications of microelectronic devices and micro-electromechanical systems (MEMS) in different areas of science, technology, and medicine [1,2]. The development and precise functionality of devices at cryogenic temperatures require the detailed knowledge of physical parameters of different materials, even in the case of MEMS. For instance, little data exist about carrier concentration and mobility in bulk silicon and diffused silicon layers down to liquid helium temperature (T = 5 K). This makes, among others, applications of technology computer-aided design (TCAD) simulation tools for device development difficult. The present paper deals with experimental measurements (Hall measurements) of carrier concentration and mobility in the temperature range 0.3 K $\leq T \leq$ 300 K. Results are compared with reference data given in the literature. The effect of the observed data on TCAD simulation results is discussed.

2. Experimental Details

Different silicon materials have been used for experiments including n-type (phosphorous doped, 8×10^{12} cm^{-3} $\leq$ P $\leq$ 3×10^{18} cm^{-3}) and p-type materials (boron doped, 7×10^{12} cm^{-3} $\leq$ B $\leq$ 5×10^{16} cm^{-3}). Hall structures and different types of diodes were prepared on such wafers (diameter 100 mm) using typical CMOS processes. Hall measurements were carried out in the temperature range 5 K $\leq T \leq$ 300 K and at magnetic fields up to 1 T. Resulting carrier concentrations at room temperature were compared to data obtained by secondary ion mass spectroscopy (SIMS).

Measurements of the current-voltage (I–V) characteristics of different diodes were realized in the temperature range 0.3 K $\leq T \leq$ 520 K. The large temperature range required different setups for preparation and measurement. An overlap of measurements in different temperature ranges was necessary to combine all data.

Different semi-classical and quantum mechanical simulation tools were applied to simulate the I–V characteristics of diodes. Simulations showed that the precise knowledge of carrier concentration and mobility is important even in the low-temperature regime.

3. Carrier Mobility and Concentration

Figure 1 shows results of measurements of electron and hole mobilities at 300 K in comparison to reference data given in the literature [3,4]. For electrons, the experimental data follow the reference data except on low dopant concentrations ($C_P \leq 2 \times 10^{13}$ cm^{-3}), where higher mobilities are measured. On the other hand, significant differences are obtained for hole mobilities at $C_B \leq 1 \times 10^{16}$ cm^{-3}. Slightly lower values of the hole concentration are measured for moderately doped materials (1×10^{14} cm^{-3} $\leq C_B \leq$ 1×10^{16} cm^{-3}), while higher values are determined at extremely low dopant concentrate ($C_B \leq 2 \times 10^{13\cdot}$cm^{-3}).

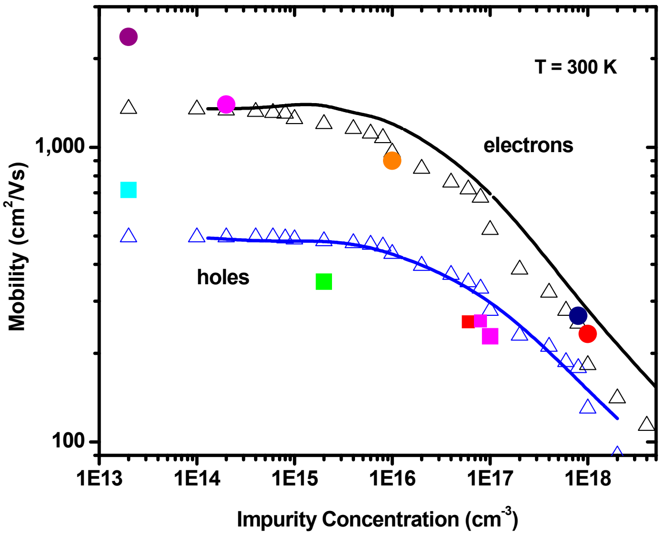


Figure 1. Measured electron (full circles) and hole mobilities (full squares) in comparison to reference data given in the literature (lines according to [3] and open triangles to [4]). T = 300 K.

Temperature-depended mobilities for holes and electrons are shown in Figure 2. The increase of mobilities of both types of carriers with decreasing temperature is clearly shown. Furthermore, mobilities also depend on the carrier concentration. The mobility decreases at a given temperature with increasing dopant concentration. The effect is more pronounced for electrons. Recent TCAD tools contain numerous models to calculate carrier mobilities. The model of Klaassen [5,6], however, is most frequently applied to simulate temperature-dependent and concentration-dependent mobilities. It includes lattice, donor, and acceptor scattering. Electron-hole scattering is also considered. Calculated mobilities using the Klaassen model agree well with experimental data measured in the temperature range 30 K $\leq T \leq$ 300 K. Decreasing temperatures, however, may cause differences between experimental and simulated mobility data. The reason is the freezing out of carriers with decreasing temperature.

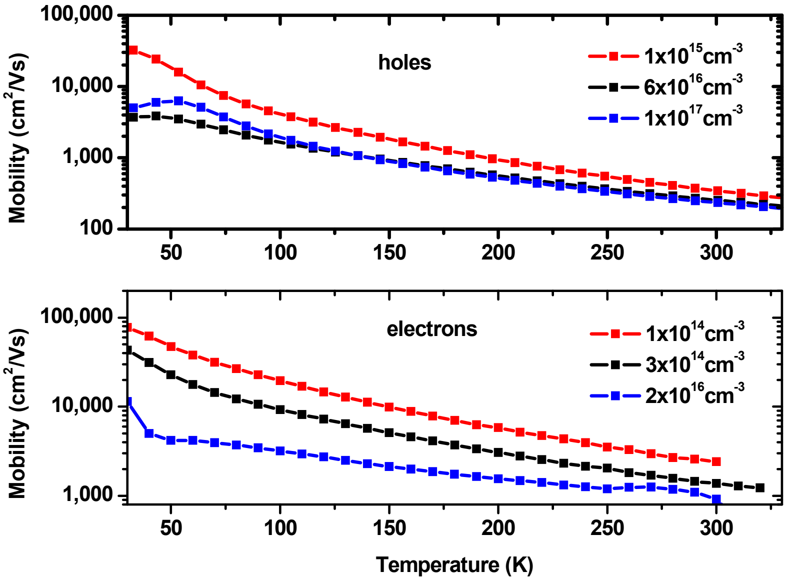


Figure 2. Temperature-dependent hole (**top**) and electron mobilities (**bottom**) of silicon with different doping levels specified in the figure.

The dependence of the carrier concentration on the temperature is presented in Figure 3 for different n- and p-type materials. Data of the carrier concentration are displayed in the Figure as relative values in relation to data at T = 300 K, which more clearly demonstrates the effect of freeze-out. The presented data explicitly show that freeze-out causes a continuous decrease of the carrier concentration with decreasing temperature for both material types. The decrease of the carrier concentration starts already at higher temperatures (around 300 K) and is much stronger for lower doping levels. For instance, nearly all dopants are not ionized already at temperatures of about 200 K for p-type material having an initial dopant concentration of $C_B \cong 2 \times 10^{12}$ cm^{-3}. The freeze-out phenomenon is described in semi-classical TCAD simulation tools on the Fermi–Dirac statistics [7]. The carrier density in semiconductors (required to solve the Poisson equation) is

$$\rho(x) = q\left[n_P - n_e + N_D^+ - N_A^-\right] \quad (1)$$

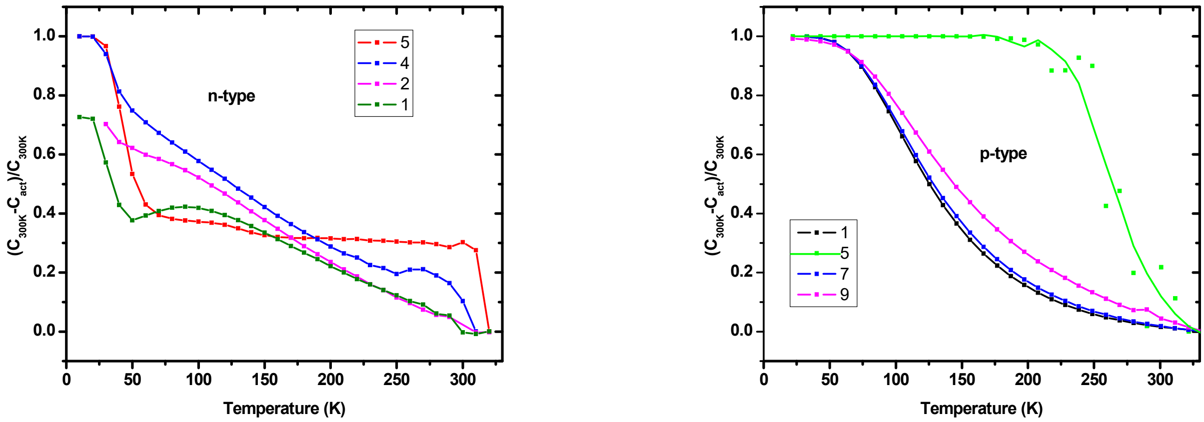
where q is the elementary charge, n_P and n_e are the densities of holes and electrons, respectively, and N_A^- and N_D^+ are the concentrations of ionized acceptors and donors, respectively:

$$N_A^- = \frac{N_A}{1 + 4 \cdot exp\left[\frac{E_A - E_{FP}}{kT}\right]} \quad N_D^+ = \frac{N_D}{1 + 2 \cdot exp\left[\frac{E_{Fn} - E_D}{kT}\right]} \quad (2)$$

The concentrations of holes and electrons in Equation (1) are

$$n_e = n_i \frac{\exp\left[\frac{E_{Fn} - E_i}{kT}\right]}{\xi\left[\frac{E_{Fn} - E_C}{kT}\right]} \quad n_P = n_i \frac{\exp\left[\frac{E_i - E_{Fp}}{kT}\right]}{\xi\left[\frac{E_V - E_{Fp}}{kT}\right]} \quad (3)$$

E_{FP} and E_{Fn} are the quasi-Fermi levels of holes and electrons. E_A and E_C are the band edges of the valence and conduction band, respectively. E_I characterizes the intrinsic Fermi level. The described formalism of Jaeger and Gaensslen [7] was applied to simulate the temperature dependence of the transconductance of SOI MOSFETs [8]. The calculated data agree with measurements down to about 100 K. Differences exist at lower temperatures referring to basic problems of semi-classical device simulations. For instance, photoluminescence data and conductivity measurements refer to large amounts of non-ionized dopants already at room temperature [9,10]. In addition, Hall measurements demonstrated a strong effect of incomplete ionization in compensated boron and phosphorous doped silicon [11]. The dependences of the freeze-out on the concentration and type of the dopants make the application of semi-classical tools questionable for low-temperature simulations. An alternative is quantum mechanical device simulations.



(**a**) (**b**)

Figure 3. Measured carrier concentration (relative values) of various n- (**a**) and p-type silicon materials (**b**) in dependence on the temperature. The relative values are the actual concentration at temperature T in relation to room temperature values ($(C_{300K} - C_{act})/C_{300K}$). The carrier concentrations at T = 300 K are for n-type materials (1) 1×10^{18} cm^{-3}, (2) 1×10^{18} cm^{-3}, (4) 1×10^{16} cm^{-3}, (5) 2×10^{13} cm^{-3}, and for p-type materials (1) 2×10^{16} cm^{-3}, (5) 2×10^{12} cm^{-3}, (7) 2×10^{16} cm^{-3}, and (9) 3×10^{16} cm^{-3}.

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